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14. ABSTRACT
CUSat is Cornell University's entry in the University Nanosatellite Program (UNP4). The student team has met many of the objectives of the program already, including education and outreach. The project promises a first-ever, end-to-end in-orbit inspection system. With centimeter-level accuracy, carrier-phase differential GPS enables CUSat to navigate and use its cameras to gather target-satellite imagery. In the ground segment, image-processing techniques verify the CDGPS position and orientation estimates and provide a 3D model of the target satellite for the data end-user.

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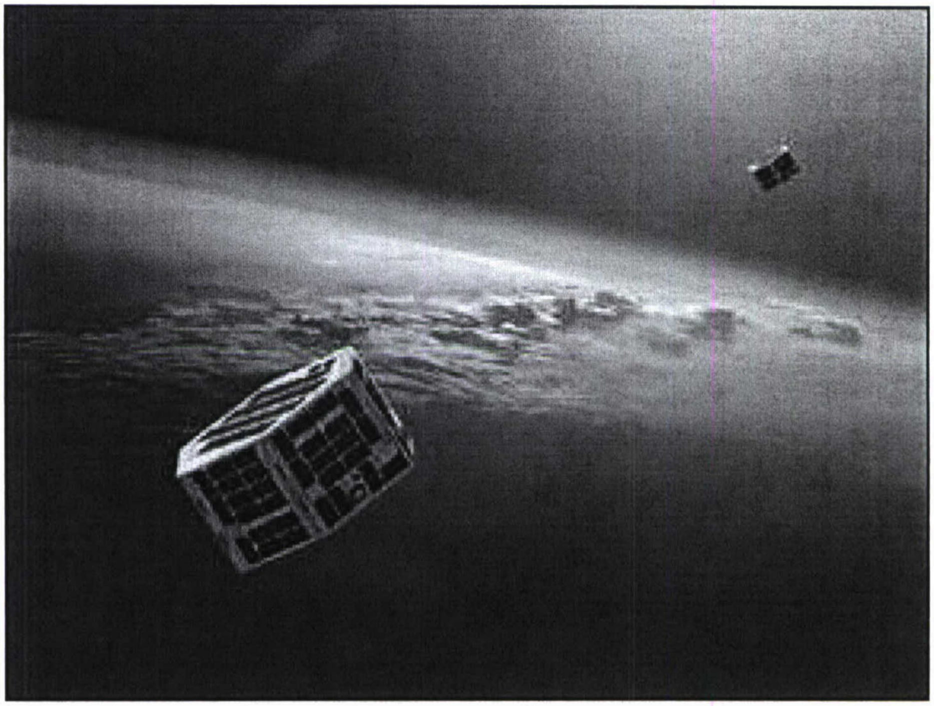

CUSat: An End-to-End In-Orbit Inspection System University Nanosatellite Program

Annual Performance Report 2007

Prepared for the Air Force Office of Scientific Research
University Nanosatellite Program 4

Grant No. FA9550-05-1-0280

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1.0 Objectives

The CUSat project includes many objectives, both programmatic and technical. The following description of these objectives includes a brief explanation of their relevance to our sponsors. The programmatic objectives (POs) are laid out in the Nanosat-4 User's Guide (UN4-001 Rev-March 2005):

- PO 1: Educational outreach to students in grades K-12
- PO 2: Attendance and participation at program Milestone Events
- PO 3: Student involvement
    - PO 3.1: Involvement of students at all levels of the Nanosat program, including management, engineering, test, and hardware assembly. Universities are expected to have a student Program Manager.
    - PO 3.2: Involvement of students from a range of engineering and other disciplines.
    - PO 3.3: Involvement of students at various education levels, (e.g. undergraduate and graduate).
    - PO 3.4: Students are expected to present their designs at all design reviews.

CUSat's technical objectives (TOs) are the following:

- TO 1: Demonstrate an end-to-end in-orbit inspection system

  Here, "end-to-end," refers to the scope of the in-orbit inspection architecture. CUSat includes a space segment, a ground segment, and a data segment. Taken as a whole, these segments form an in-orbit inspection system that autonomously images a target spacecraft, downlinks this imagery to the ground, recovers a three-dimensional shape from these images, and conveys them in a responsive manner to data end users.

- TO 1.1: Demonstrate space-segment technologies for in-orbit inspection

  These technologies address several Air Force and NASA needs, including responsiveness, robustness, and safety.

    - TO 1.1.1: All-GPS guidance and navigation

      GPS is a technology that is largely platform independent and works well for precision navigation (both absolute and relative) in a variety of orbits. Other technologies, such as earth sensors and star trackers, have their appropriate applications but are not sufficiently broad in their applicability for CUSat's purpose. This purpose is to serve as demonstration of a turn-key inspection system, one that can be used for many different spacecraft without time-consuming and risky modifications. CUSat's generic design demonstrates responsiveness in that missions that demand an inspection capability can use an off-the-shelf CUSat design rather than a custom one. The low cost of an all-GPS system is another important reason for CUSat's implementation of it, given our cost constraints, but this demonstration can also enable future low-cost missions.

- TO 1.1.2:Autonomous navigation with carrier-phase differential GPS (CDGPS)

  Navigation here refers to the estimation and control of position, along with higher-level decision functions.

- TO 1.1.3:Attitude determination with CDGPS
- TO 1.1.4:Fault-tolerant inspection architecture

  Meeting this objective will demonstrate that a low-cost system can be fault tolerant without depending on redundant devices, but rather by cross-strapping critical functionality among multiple subsystems.

- TO 1.1.5:Collision-Free Navigation

  This objective is achieved as a combination of functions, including the mission design (orbit mechanics), fault tolerance, and precision navigation

- TO 1.2: Demonstrate ground-segment technologies for in-orbit inspection.
  - Demonstrate ground operations for autonomous inspection

    CUSat's concept of operation is designed to reach the "sweet spot" of combined autonomy and ground-controller interaction. The ground will be responsible for decisionmaking regarding changes in mission phase (such as separation or anomaly resolution) but not in the day-to-day activities. The telemetry and command system is based on providing data for diagnosis of CUSat's health and a small number of critical commands and uploads but not for realtime "joystick" control.

  - Demonstrate a responsive, distributed ground segment

    Northrop Grumman Mission Systems (NGMS) has partnered with CUSat, offering access to some of its ground-station assets. NGMS will work with CUSat to develop a means of conveying data among at least three ground stations (one in Southern California, one in Colorado, and one in Ithaca, NY) ina way that allows a distributed end-user community to access the inspection data.

- TO 1.3: Demonstrate data-segment technologies for in-orbit inspection.

  CUSat will demonstrate the use of familiar image-processing techniques to create a three-dimensional shape from still images taken in orbit. These algorithms will run within the ground-station software. This surface-map data will serve as the primary data product for end users. The design of the spacecraft will be such that it can be analyzed by these imaging techniques.

- TO 2: Demonstrate Nanosatellite Technologies

  CUSat uses a number of approaches from other small satellites. Those heritage solutions do not represent significant value as demonstrations. However, we will demonstrate three unique technologies.

  - Demonstrate the ACS-in-a-box device (the IMI-C) from Intellitech Microsystems Inc.. This device consists of three reaction wheels, three mag torquers, a threeaxis magnetometer, a sun sensor, and an earth sensor. CUSat will demonstrate its functionality, but the system will be able to perform without this device.

- Demonstrate rapid, modular assembly. A key element of responsive space, this demonstration will be realized via the design of CUSat's electronics backplane, which includes modular, common connectors and a mechanical strategy for mounting electronics cards within common-sized shielding boxes. These components can be removed and replaced with relative ease.
- Demonstrate an all-propulsive, pulsed-plasma thrustser (PPT) attitude-control system. While the IMI-C provides CUSat with considerable functionality, the baseline design includes eight PPTs, in an eight-for-seven redundant attitude- and position-control actuator suite. The safety of these non-combustive, lightweight devices makes them ideal for inspection of manned spacecraft.
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2.0 Status of Effort

CUSat is a multi-year effort to design, build, and launch an autonomous on orbit inspection satellite system. CUSat is a student project team in the College of Engineering and is part of the University Nanosat-4 Competition, a two year, cyclic program run by the Air Force Research Lab (AFRL). For the University Nanosat Competition, student teams design their own mission and build a satellite to perform their mission. Each team goes through several design reviews by the AFRL, leading up to a final review in which a single winning team is chosen. This team receives additional support from the AFRL and is given a launch opportunity.

Mission and Operations

CUSat is Cornell University's entry into the University Nanosat Competition. CUSat's mission is defined as follows:

CUSat demonstrates an end-to-end autonomous on orbit inspection system. Centimeter-level accurate Carrier-phase Differential GPS (CDGPS) enables CUSat to navigate and use its cameras to gather target-satellite imagery. In the Ground Segment, image-processing techniques verify the CDGPS relative distance and orientation estimates and provide a 3D model of the target satellite for the user.[1]

The primary goal is to demonstrate cooperative, on orbit inspection. The driving technology that helps to achieve this goal is Carrier-phase Differential GPS, a differential GPS technique that allows measurement of relative vectors between antennas with better than 1cm accuracy. By using two identical satellites with three GPS antennas each, CUSat is able to measure relative vectors between the two satellites and gain an attitude estimate of each individual satellite. This data is used to direct visual inspection using on-board cameras. The acquired images are then downlinked to a ground station for 3D reconstruction.
Both satellites will launch in a single stack as a secondary payload on the launch vehicle. After separation from the launch vehicle, the stack will power on and begin to charge its batteries. The stack will then initiate ground communication. After a system checkout, the ground will issue a command for the stack to separate. Once separation has occurred, the satellites will enter an autonomous inspection mode where pictures are taken automatically when the opportunity arises. The ground stations will then request these images for download. [2]

Program Structure

CUSat has historically followed a project-oriented structure. Professor Mason Peck, the Principal Investigator, is in charge of all project operations. The Program Manager, typically a student who has been with the program for a long time, reports to Professor Peck. Work on CUSat is then divided up into several subsystems. Each subsystem has a lead which reports to the Program Manager.

Program Schedule and Milestones

The AFRL specifies that the following reviews take place for all entrants to the competition:

- Systems Concept Review – May 2005
- Preliminary Design Review – August 2005
- Critical Design Review – February 2006
- Proto-Qualification Review – August 2006
- Flight Competition Review – March 2007

In addition to these reviews, CUSat conducted several internal reviews described later in this report.

Design Maturity

CUSat delivered one fully functional prototype flight unit for the Flight Competition Review (FCR). This unit contained a complete and functional electrical bus. Most custom printed circuit boards (PCBs) were professionally populated by Northrop Grumman Space Technology, the remainder were assembled in-house. The proto-flight unit also contained a complete structure. Most structural components were machined in-house. Several components were manufactured by Moog, Inc. Space Systems. Since the proto-flight hardware was intended to be used for the actual flight units, all of it was appropriately tracked per the CUSat Configuration Management and Quality Assurance (CM/QA) Plan.

On the subsystem level, the vast majority of hardware was delivered except for several large ticket items. These large-ticket items included the inter-satellite Motorized Lightband Separation System, flight solar cells and solar cell honeycomb panels. Most of these were excluded because of budget constraints.

The purpose of the prototype build was to demonstrate the ability of the team to deliver functional, high quality hardware. Another purpose of the prototype was to identify any integration issues and unresolved design issues.

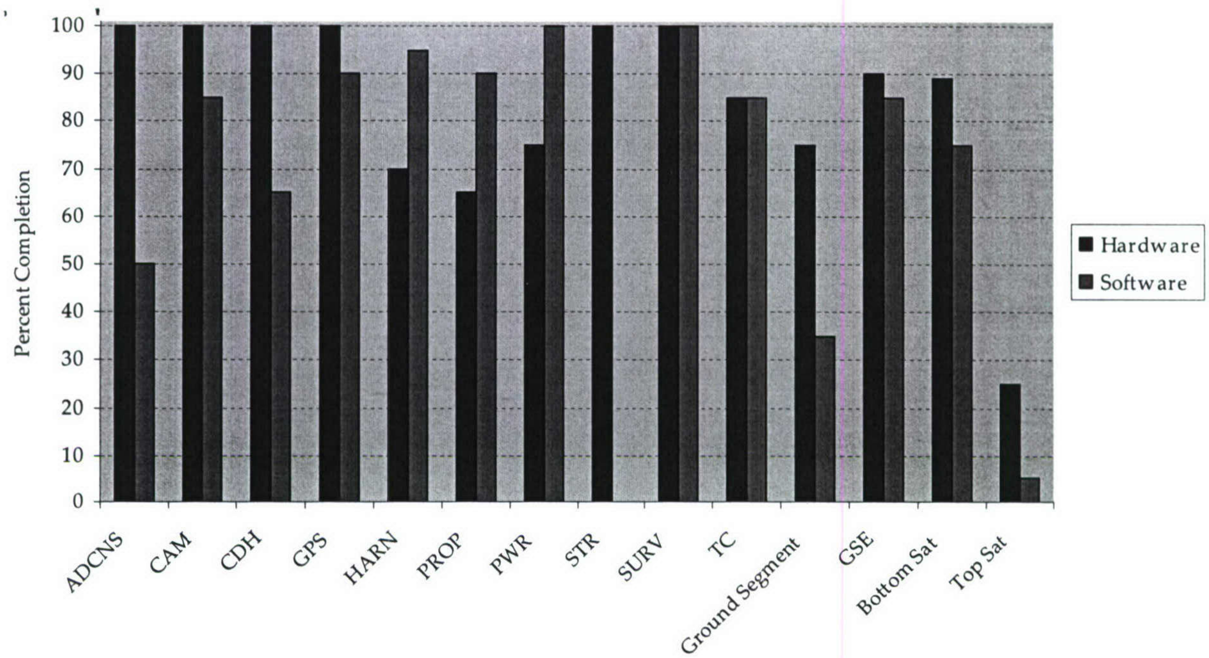


Figure 1 - FCR Hardware Design Maturity [3]

Flight Competition Review (FCR)

The Flight Competition Review served as a major design review milestone. However, the main purpose of the review was to allow the AFRL to choose a winning team to which they would offer continued support and a launch opportunity. For the competition, one of the author's main responsibilities was to develop a plan to complete the program upon a win at FCR. This document was labeled the *Post-FCR Action Plan* (CUSAT-SYS-0026)[3] and constitutes a large portion of the work for the initial sections of the report.

Cornell's entry was chosen as the winner of the competition based on technical merit, relevance to the AFRL, program documentation, as well as several other factors. As a result of this decision, the AFRL committed to supporting the program through completion. This necessitated heavy planning for delivery of hardware qualified for space flight, software that was thoroughly tested, and a ground support system capable of running the mission.

Program Deliverables and Goals

Completion of the CUSat program is contingent upon delivery of several large items:

- *Flight Hardware*

  Two identical satellite units that satisfy the hardware requirements set forth in the CUSat Requirements document. Problems identified with the proto-flight unit needed to be fixed, whether by physical changes to the hardware or modifications to the design. Additionally, a full two sets of flight hardware plus several spare pieces of hardware needed to be manufactured. Hardware delivery is contingent upon a successful integration process as well as a rigorous and well documented testing process.

- *Flight Software*

  Flight software includes embedded code for smaller systems, baseline code for the flight computer, high-level control code, as well as filters, estimators, and controllers. All of this software needs to be verified on the ground through a combination of simulation and test.

- *Ground Stations*

  Well designed and maintained ground stations are essential for mission success. Final delivery requires that ground stations be ready to receive telemetry and send commands. A central server and ground station network also needs to be complete. Hardware acquisitions (such as antennas) are also key to ground station delivery.

- *Mission Operations*

  Well defined operating procedures as well as trained operators are also critical for mission success. Part of the overall delivery package includes a team capable of handling routine as well as unforeseen operating conditions for the lifetime of the CUSat mission. This team needs to maintain knowledge across generations of graduates.

Scope of this Report

The scope of this project includes work done by the author after the Flight Competition Review (FCR). At this point, the project had been in progress for about two years. This project focused on bringing a prototype system through delivery as a flight-ready, robust, tested system. The report is split into four sections.

Program Management

Leading the CUSat team towards completion of the flight units was the primary purpose of this project. The report details planning for the flight build as well as several reviews and other tools that were used to accomplish goals set forth in the beginning of the semester. Regular communication between the AFRL, the University, Professor Peck, and team members was also a key part of the project. Program schedule, budget, and organization are all covered in this section of the report.

Camera Interface Board (CAM IB)

This semester, a lot of technical work was done to redesign the Camera Interface Board (CAM IB) after identifying serious design flaws during FCR. This section of the report outlines system requirements, describes the design process, and shows how the design met the requirements.

Power Board Completion

Power board design was done as a senior honors project. FCR integration exposed several design flaws with the safety inhibit design. These flaws were addressed as part of this project. The updated design is described in this section of the report.

System Level Trade Studies and Analysis

This project also dealt with several system-level design decisions. There were also several specific design tasks relating to hardware work. All of these tasks contribute to the larger goal of creating a flight-ready system to meet program requirements and accomplish mission objectives.

Program Management

This section details the work done to plan for final delivery to the AFRL. A large portion of this work was done before FCR to demonstrate the ability of our program to finish and our desire to deliver a complete, functional system. Planning was required on several levels. First, a budget needed to be developed to ensure that delivery was not impeded by funding constraints. Also, a large portion of the team was graduating at the end of the year, so a well thought-out recruitment effort was essential to continued program success. Remaining design work from issues identified during FCR also needed to be planned for. Finally, the extensive integration and testing process needed to be spelled out and scheduled to ensure success.

Post-FCR Action Plan

The *Post-FCR Action Plan[3]* was a major first step in the planning process. A current budget was presented to demonstrate the ability to finish the program given extended AFRL funding. Remaining build and design issues were also presented to give an honest yet hopeful timeline for flight unit delivery. An assembly, integration, and test (AI&T) schedule was also presented to show our expected completion time.

Project Level Goals

The following goals were identified as necessary for successful project completion:

1. *Resolve remaining design issues identified after FCR.*

During the prototype build, several design issues were identified. These ranged in severity from very minor (improperly sized bolts) to severe (lack of ability to build solar panels). To ensure successful resolution of these issues, a post-FCR debriefing meeting was held. A system-wide list of outstanding actions was assembled and specific actions were assigned to specific team members. Team members were informed that their grade for the coming semester directly depended on their ability to resolve these issues.
Several issues were identified as beyond the scope of a particular subsystem or beyond the expertise of certain team members. These issues included:

- Solar Panel Construction
- Communications Antenna Design

These trades are addressed directly later in this report.

2. *Finish machining of structural and propulsion components.*

Design of a machining schedule and finalization of part drawings was assigned to Ofer Eldad, the mechanical lead. With Ofer's guidance, the structural design and manufacturing teams on CUSat were was able to lay out a machining schedule and finish major machining efforts on time.

3. *Finish design and build of electrical subsystems.*

Several electrical systems required direct attention. These included:

- Camera Interface PCB
- Propulsion Electronics
- Power PCB Redesign

These designs are addressed directly later in this report.

4. ***Rigorously test subsystem hardware.***

5. ***Integrate and test all hardware to verify system requirements.***

While test plans had been developed before FCR, most of them had not been run on hardware and were inadequate for requirement verification. Part of the work done this semester included setting up a testing process and training new members to carry out the tests.

6. ***Maintain a program budget to ensure adequate funding.***

An overall budget was developed as part of the Post-FCR Action Plan. This is included in this report.

7. ***Develop comprehensive ground support and mission operations systems and train personnel.***

Two major milestones for the ground segment this semester were acquisition of ground station software and the formation of the mission ops team. A mission ops team was formed this semester with the goal of developing a coherent set of recommended operating procedures (ROPs) for ground station operation. Ground station software trades are discussed later in this report.

Budget

A forward looking budget was developed for the Post-FCR Action Plan. Each foreseen expenditure was listed by subsystem. The results are summarized in Table 1.

Table 1 - Preliminary Budget [3]

Subsystem	Resources Required	Cost
ADCNS	None	$0
	$0	
CAM	Additional Cameras	$5,000
	Additional FPGA Boards	$3,500
	Lenses	$2,550
	$2,550	
CDH	Additional Flight Computer	$550
	$550	
GPS	None	$0
	$0	
HARN	Additional Connectors/Supplies	$500
	Fabrication of Flight PCBs	$4,000
	$4,500	
I&T	Support Equipment/Materials	$5,000
	$5,000	
PROP	PPU Electronics Fabrication	$4,000
	PPT Stock/Manufacture	$500
	PPT Wiring Harness	$2,500
	Busek Testing	$500
	$4,500	
PWR	Fabrication of Flight PCBs	$2,000
	Solar Cells	$76,750

	$108,750	
T&C	Fabrication of Flight PCBs	$1,000
	Antenna Fabrication	$500
	$1,500	
STR	Honeycomb Panels	$5,000
	Motorized Lightband	$80,000
	$225,000	
GS	Antennas/RF Equipment and Computers	$0
	MAESTRO and GUI	$0
Other	Other Expenses	$10,000
	$10,000	
Total Program Cost Remaining: **$208,350**		

Personnel

A large number of experienced CUSat members were graduating at the end of the spring semester. In order to mitigate the risk of losing knowledge, an aggressive recruitment process was started before the end of the semester. Team leads were asked to submit a list of jobs that needed to be filled. Several information sessions were run and advertisements were put out to attract new students to the team. Students were encouraged to fill out an application form and submit it to the team leadership. After interviewing prospective candidates, the team leads were asked to submit a list of candidates that they wanted to accept.

In order to acclimate new members, an orientation session was run. This consisted of a Powerpoint presentation that described the team history, progress, documentation procedures, and how to use the team website. New members were assigned documentation to read before starting work [4].

Schedule

A long term delivery schedule was designed for the Post-FCR Action Plan. The schedule sets hardware delivery in January of 2008. The AFRL has requested that we stick to this schedule and deliver flight hardware between January and March of 2008.

ID	Task Name	Duration	Start	Finish
1	**Flight Competition Review**	**0 days**	**Sun 3/25/07**	**Sun 3/25/07**
2	**Final Design Review**	**0 days**	**Fri 6/15/07**	**Fri 6/15/07**
3	**Pre-Ship Review**	**0 days**	**Mon 11/12/07**	**Mon 11/12/07**
4	**Operational Readiness Review**	**0 days**	**Wed 12/12/07**	**Wed 12/12/07**
5	**Flight Readiness Review**	**0 days**	**Mon 1/28/08**	**Mon 1/28/08**
6				
7	**Hardware Delivery**	**206 days**	**Sun 3/25/07**	**Fri 1/4/08**
8	**Solar Panels**	**140 days**	**Sun 3/25/07**	**Thu 10/4/07**
9	Finalize Cell Layout & Place Order	1 mon	Sun 3/25/07	Thu 4/19/07
10	Panel Fabrication Delivery/Fab	6 mons	Fri 4/20/07	Thu 10/4/07
11				
12	**Lightband**	**140 days**	**Sun 3/25/07**	**Thu 10/4/07**
13	Order Lightband from PSC	1 mon	Sun 3/25/07	Thu 4/19/07
14	Lightband Delivery from PSC	6 mons	Fri 4/20/07	Thu 10/4/07
15				
16	**Custom PCBs**	**65 days**	**Sun 3/25/07**	**Thu 6/21/07**
17	Finalize Design	4 wks	Sun 3/25/07	Thu 4/19/07
18	Reorder PCBs	10 days	Fri 4/20/07	Thu 5/3/07
19	Fab and Test EDU Parts	1 wk	Fri 5/4/07	Thu 5/10/07
20	Fabrication by NGST	1 mon	Fri 5/11/07	Thu 6/7/07
21	Functional Checkout	2 wks	Fri 6/8/07	Thu 6/21/07
22				
23	**COTS Components**	**40 days**	**Sun 3/25/07**	**Thu 5/17/07**
24	Finalize and Place Order	1 mon	Sun 3/25/07	Thu 4/19/07
25	Prep Parts at NGST	1 mon	Fri 4/20/07	Thu 5/17/07
26				
27	**Mechanical Parts**	**30 days**	**Sun 3/25/07**	**Thu 5/3/07**
28	Refab of CDH Box	5 wks	Sun 3/25/07	Thu 5/3/07
29	Alodine/Anodize Parts	1 mon	Sun 3/25/07	Thu 4/19/07
30	Finish PPTs	4 wks	Sun 3/25/07	Thu 4/19/07

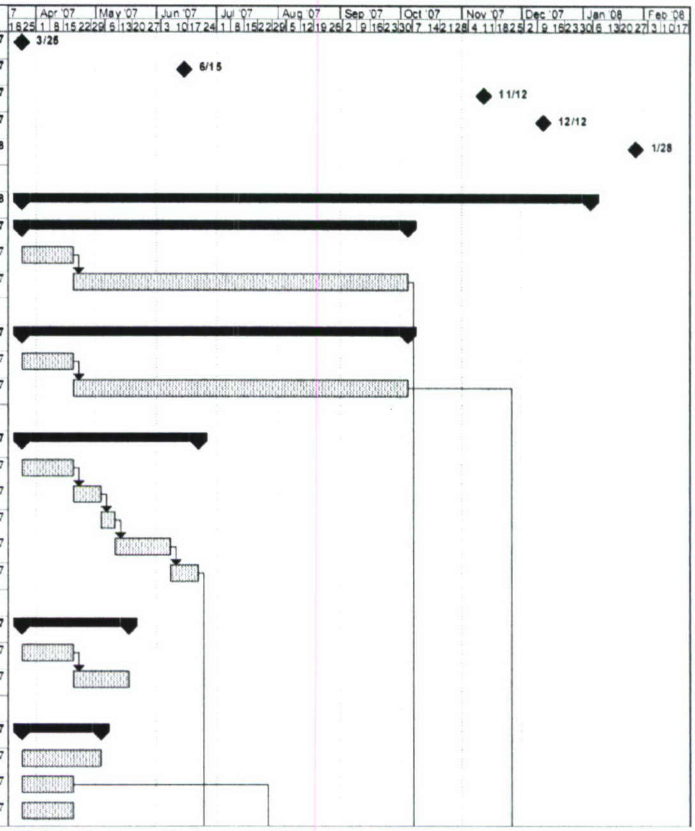


Figure 2 - Post-FCR System Schedule [3]

ID	Task Name	Duration	Start	Finish
31				
32	**Flight Build**	**141 days**	**Fri 6/22/07**	**Fri 1/4/08**
33	Electronics Bus AI&T	5 wks	Fri 6/22/07	Thu 7/26/07
34	Wall/Stiffener AI&T	3 wks	Fri 7/27/07	Thu 8/16/07
35	Propulsion AI&T	2 wks	Fri 8/17/07	Thu 8/30/07
36	Camera AI&T	2 wks	Fri 8/31/07	Thu 9/13/07
37	Battery Box AI&T	2 wks	Fri 9/14/07	Thu 9/27/07
38	Solar Panel AI&T	2 wks	Fri 10/5/07	Thu 10/18/07
39	T&C Antenna AI&T	3 days	Fri 10/19/07	Tue 10/23/07
40	GPS Antenna AI&T	3 days	Wed 10/24/07	Fri 10/26/07
41	Half-Sat Checkout Tests	2 wks	Mon 10/29/07	Fri 11/9/07
42	Ship to AEF	2 wks	Mon 11/12/07	Fri 11/23/07
43	Lightband AI&T	2 wks	Mon 11/26/07	Fri 12/7/07
44	Full System Tests	4 wks	Mon 12/10/07	Fri 1/4/08
45	Flight Unit Complete	0 days	Fri 1/4/08	Fri 1/4/08
46				
47	**Software Delivery**	**120 days**	**Sun 3/25/07**	**Thu 9/6/07**
48	Embedded Software Development	6 wks	Sun 3/25/07	Thu 5/3/07
49	Baseline Flight Code Finalization	4 wks	Sun 3/25/07	Thu 4/19/07
50	GNC Algorithm Development	4 mons	Sun 3/25/07	Thu 7/12/07
51	GNC Code Porting to Flight Computer	2 mons	Fri 7/13/07	Thu 9/6/07
52				
53	**Grounds Segment Delivery**	**100 days**	**Sun 3/25/07**	**Thu 8/9/07**
54	Ground Segment Hardware Delivery	6 wks	Sun 3/25/07	Thu 5/3/07
55	Ground Station Interface Definition	6 wks	Sun 3/25/07	Thu 5/3/07
56	MAESTRO Integration	3 mons	Fri 5/4/07	Thu 7/26/07
57	On Orbit Operations Plan	4 wks	Sun 3/25/07	Thu 4/19/07
58	Ground Segment Software Development	2 mons	Sun 3/25/07	Thu 5/17/07
59	Ground Segment Testing	2 wks	Fri 7/27/07	Thu 8/9/07

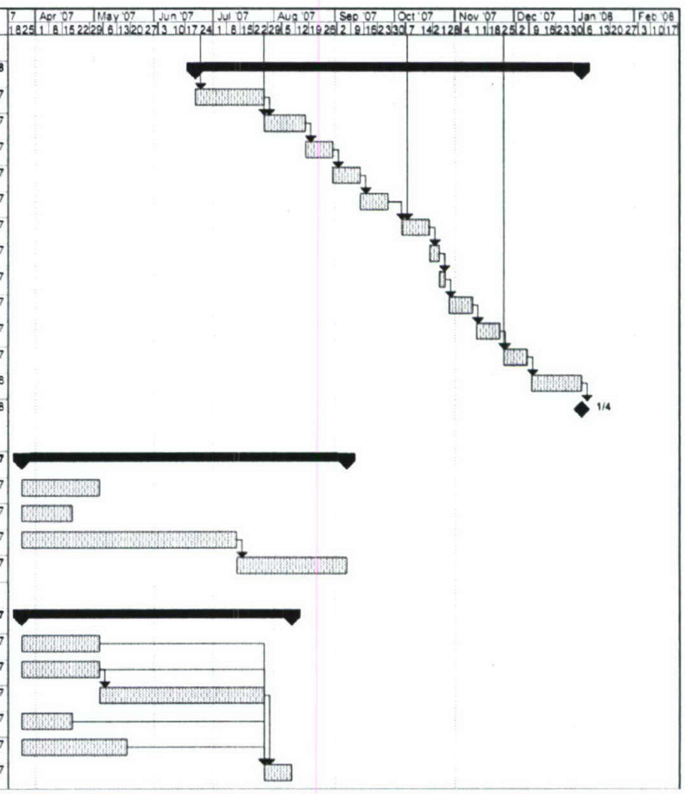


Figure 3 - Post-FCR System Schedule (ctd) [3]

While the overall program schedule was defined before FCR as shown in Figure 2 and Figure 3, a more detailed schedule was set up using Microsoft Project to keep the team on track. This schedule was kept up to date on the internal website and was updated weekly at the leads meetings. Specific tasks and deadlines were assigned directly to different team members. An example of part of this schedule is shown below in Figure 4.

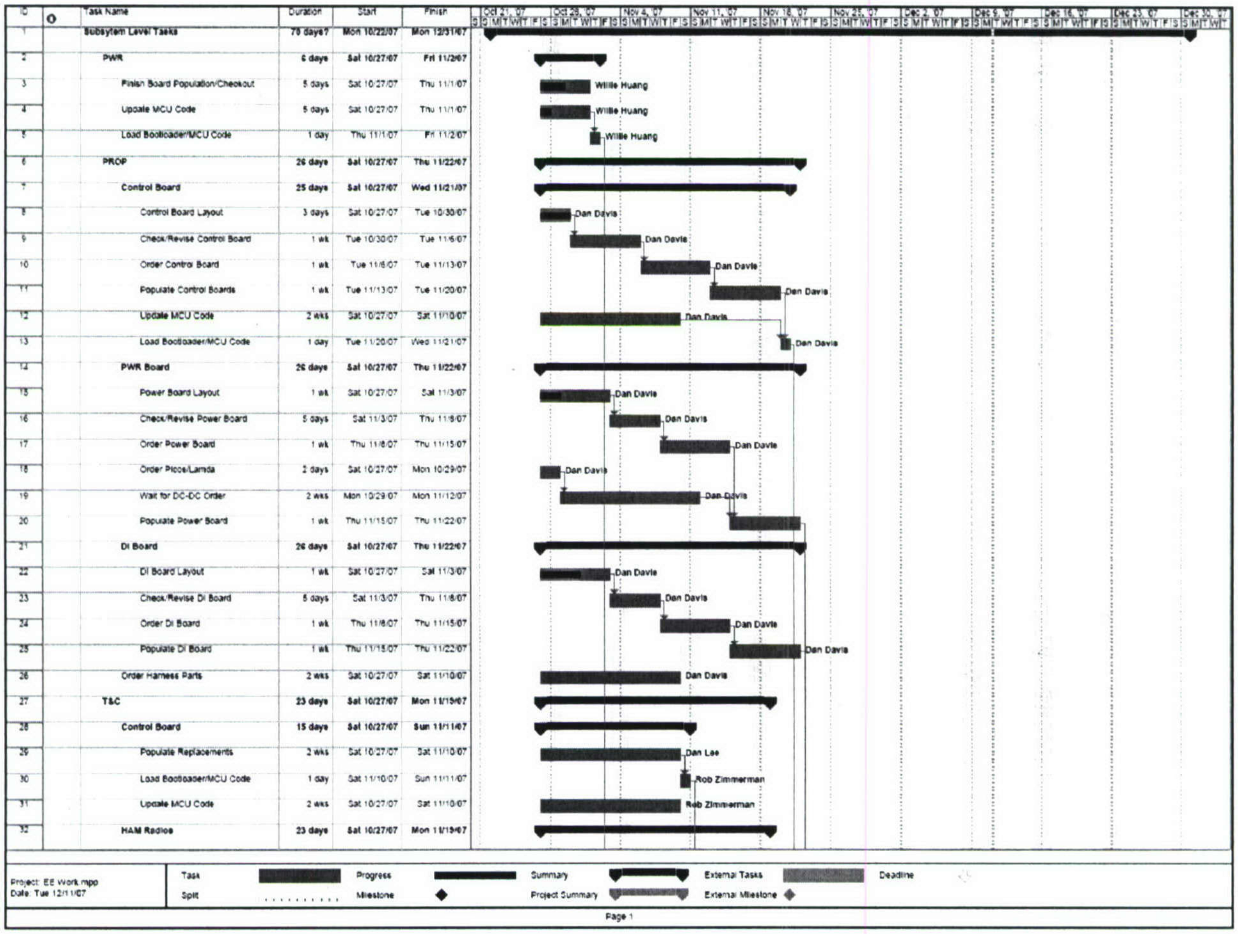


Figure 4 - Detailed Program Schedule Example [5]

In addition to tracking action items by team member and subsystem, a Hardware Status Chart was also developed. This chart gave an overall picture of the current hardware status using different colors to indicate varying levels of risk and completeness. This was particularly useful to see what parts were slipping behind. It also provided another source of schedule for team members who were averse to using Microsoft Project. An example of this is shown in Figure 5.

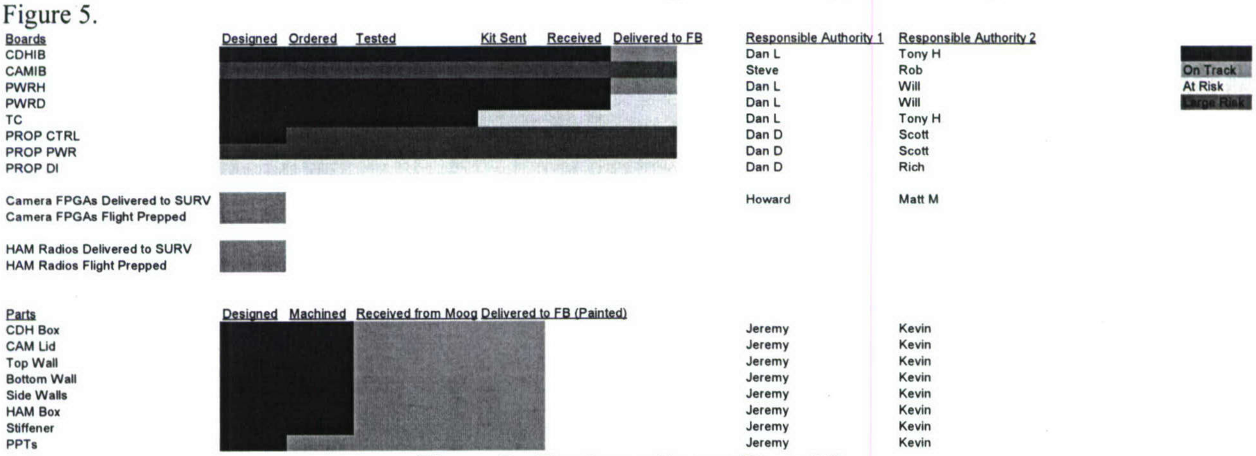


Figure 5 - Hardware Status Chart [6]

Communications

Weekly meetings were held on three levels to discuss progress and high-level issues. These meetings occurred every Monday and helped to foster communication between people working on various levels of the project.

Leads Meeting

This meeting involved all of the subteam leads. Weekly progress was discussed. This gave the leads a chance to work out some inter-subsystem issues. The system level schedule was also discussed and updated at each of these meetings. At the end of each meeting, action items were assigned to various leads.

Meeting with Professor Peck

This meeting included the PI (Professor Peck), the PM (the author), and the lead mechanical systems engineer (Ofer Eldad). The purpose of this meeting was to update Professor Peck on the team status as well as to work out high-level issues, such as those dealing with the University or the AFRL. Professor Peck would also offer technical advice when the team would encounter a particularly difficult problem.

AFRL Telecon

This weekly phone conference consisted of a small group of subteam leads as well as the lead Systems Engineer and Program Manager for the University Nanosat Program at the AFRL. The purpose of the conference was to update the AFRL as to team status and work out delivery related issues. The AFRL would also offer technical advice.

Integration and Testing

Goals

The overall purpose of the Integration and Testing (I&T) effort was to satisfy system level goal number (5). Several lower level goals were derived to accomplish this test.

1. Implement and enforce rigorous Configuration Management and Quality Assurance (CM/QA) procedures.
2. Develop meaningful test procedures that verify system and subsystem level requirements.
3. Test all flight hardware and run integration tests using rigorous test procedures.

CM/QA procedures were already well defined at the start of the project based on AFRL recommendations. The main challenge was gaining momentum in the testing area. Most I&T members were new and unfamiliar with the hardware and the testing process. To kick-start the process, the author organized and helped with several initial hardware tests. Once the testing phase had started, the I&T team members were able to continue the process and develop high-quality test procedures.

Ground Segment and Mission Operations

Up until FCR, the ground segment and mission operations had received significantly less focus than the space segment. It was recognized that these sectors of CUSat would play a pivotal role as hardware development came to an end. As a result, a large part of the team (about one third) was devoted to ground segment and mission operations work.

Reviews

Several reviews were held as stage-gates to ensure that the team was on task and to provide concrete deadlines that had to be met. Some of these reviews were on the team level, but others included industry experts and the AFRL.

Post-FCR Review

The Post-FCR Review was designed to make sure that issues identified during FCR were not ignored and forgotten. For the review, each team met with the program manager and outgoing program manager to discuss issues with their subsystem. These issues were recorded and turned into action items. This list of action items was used as the deliverable list for the subteam in the next semester. These are included in the appendix.

Red Team Review

This review took place on September 28^{th}, 2007. Attendees included industry experts and AFRL employees. The review was an all-day event that consisted of several presentations where the reviewers were encouraged to ask questions and write down action items. Presentations were design to show the current state of the program and to encourage discussion about high-risk and still unresolved issues with the design [7].

Operations ROPs Review

This internal review took place mid-semester. The purpose was to review the first draft of several of the Recommended Operation Procedures (ROPs) designed by the mission operations team. Team members gave feedback and assigned action items to each of the ROPs.

Camera Interface Board (CAM IB)

The original Camera Interface Board (CAM IB) design used four boards:

- The Heron FPGA5 board

  This board was used to capture image data from the cameras.

- The Heron Base board

  The FPGA5 board mounted directly to this board. The Base board provided power to the FPGA.

- The CAM IB

  This board interfaced between the Heron FPGA5/Base and the flight computer through the Jumper Board. It was mounted on standoffs on the side of the camera electronics enclosure.

- The CAM IB Jumper Board

  This board held the connector for the box enclosure and jumper wires from the connector to the CAM IB.

The decision was made to replace the Heron Base board as well as the side board with a single Camera Interface Board (CAM IB). See the Trade Studies section for details on this decision. The CAM IB had the following derived requirements:

1. The CAM IB shall provide all necessary functionality for the FPGA5 board originally provided by the Heron Base board.
2. The CAM IB shall provide an RS-485 link to the Heron FPGA5 board.
3. The CAM IB shall provide an interface to the flight computer as specified by the Electrical ICD.
4. The CAM IB shall be capable of reprogramming the Heron FPGA5 using JTAG.

To satisfy requirement (1), several documents from Heron were obtained [8,9,10]. These documents provided exact dimensions of the Heron FPGA5 board as well as descriptions of most of the interface pins. However, the interface used was designed for much more complicated systems and many pins were unused on the Heron Base board. A diagram of the Base/FPGA board setup is shown in Figure 6.

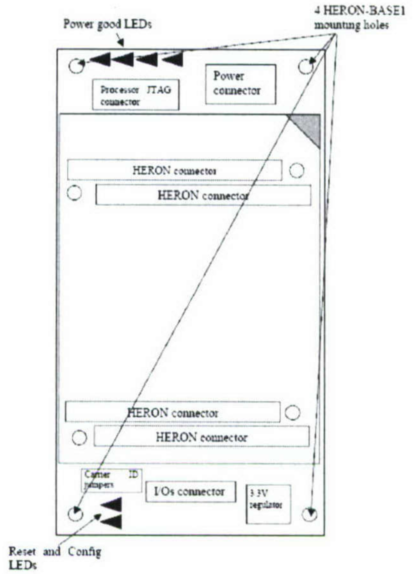


Figure 6 - Diagram of the Heron Base Board [8]

Schematic

Using the signal list from the specification, each pin on the base board was probed to measure:

- Resistance to ground
- Resistance to 5V
- Resistance to 3.3V
- Voltage when the board was powered

Unfortunately, these measurements were recorded by hand and are not included in the report. However, the circuit diagram in Figure 7 shows the results of the analysis.

This allowed the elimination of many unused features in the spec. After many checks to the recorded measurements, a schematic was drawn for the CAM IB. The schematic mimicked the connections as they were done on the Base board.

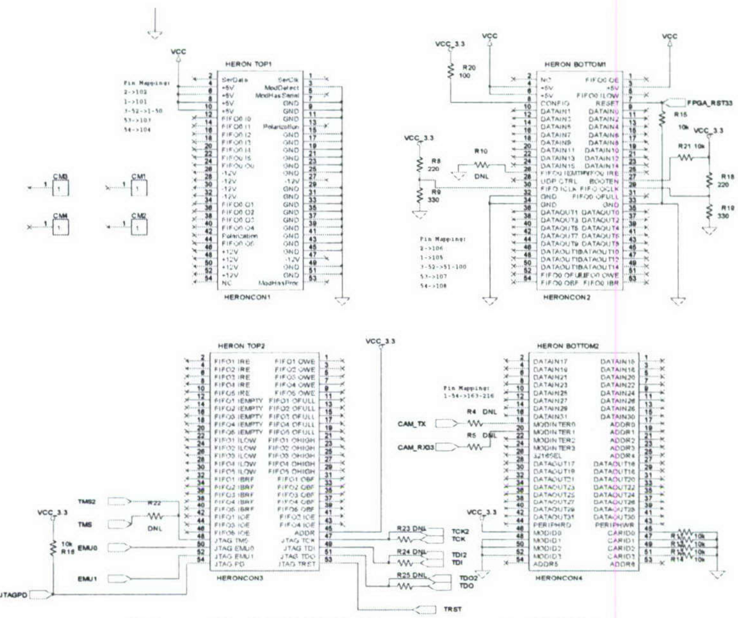


Figure 7 - CAM IB Connections to FPGA

In situations where the exact connection for a pin was unclear, several "do not load" (DNL) resistors were placed to allow the populator of the board to change the functionality if necessary.

5V and 3.3V lines were required for the CAM IB microcontroller and FPGA board. These were generated using the following circuit:

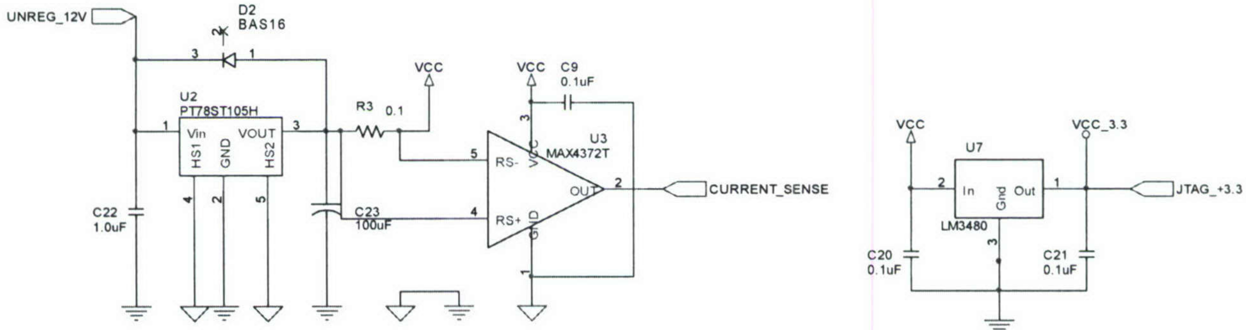


Figure 8 - CAM IB Power Regulation

The PT78ST105H is a switching regulator that outputs 5V at up to 1.5A, more than sufficient for the FPGA and microcontroller. This device is recommended by the Electrical ICD (CUSAT-SYS-011). The MAX4372T is a current-sense amplifier used to measure the current output. The LM3480 is a small package 3.3V linear regulator and was chosen since the 3.3V line is used only for low power applications. Originally a plan was in place to use separate analog and digital grounds, however there was no sensitive analog circuitry onboard, so these grounds were connected here.

For RS-485 communication, the MAX3083 chip was used as specified in the Electrical ICD (CUSAT-SYS-011). One chip was used for CUCP communication while another was used for communication with the FPGA.

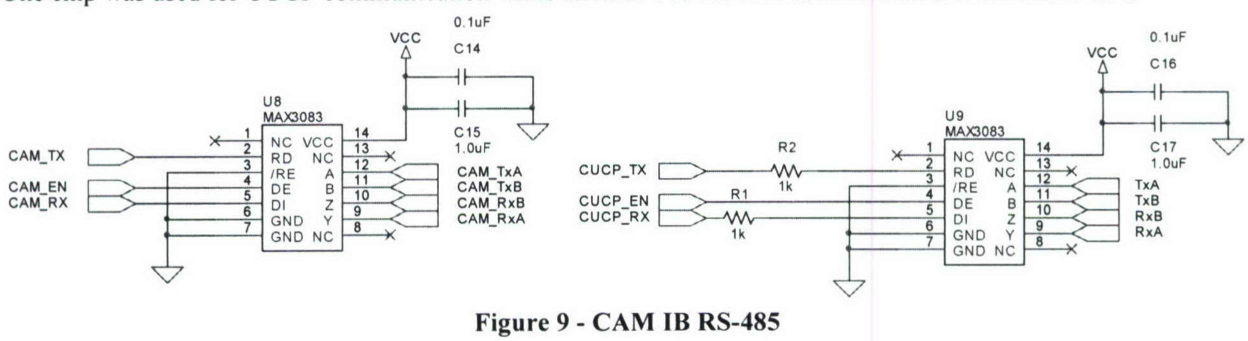


Figure 9 - CAM IB RS-485

A 5V to 3.3V level converter was required for JTAG signals and some FPGA signals, such as the reset line. A 3.3V to 5V level converter was not required since the microcontroller, which runs off of 5V, considers any level above 3.0V as "high". The TC74LCX244FT octal buffer chip was chosen as it can be used as a level converter. Enable lines were tied to the microcontroller for additional functionality.

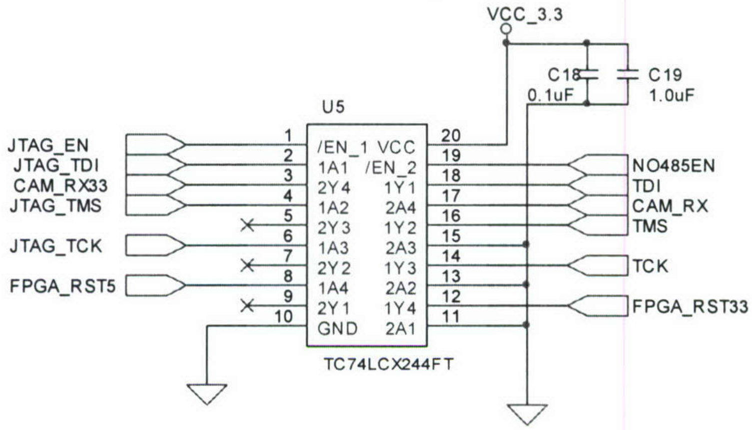


Figure 10 - CAM IB Level Converter

The microcontroller used was the Atmel ATMEGA128, as specified in the Electrical ICD (CUSAT-SYS-011). All control and sensor lines were hooked up to the microcontroller.

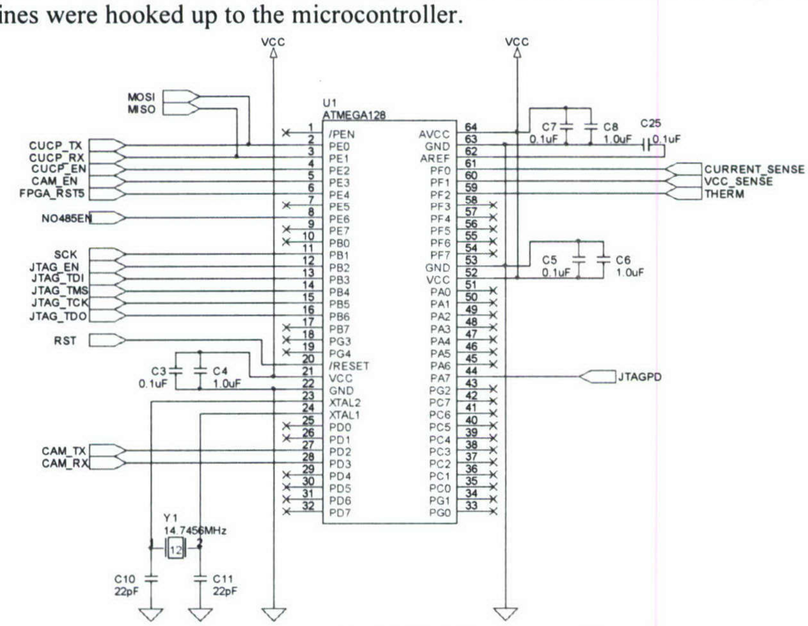


Figure 11 - CAM IB Microcontroller

The layout of the camera enclosure box required the construction of a jumper board to hold the backplane connector. To save money, this board was built as part of the CAM IB and the two boards were cut apart before population. The jumper schematic is shown here:

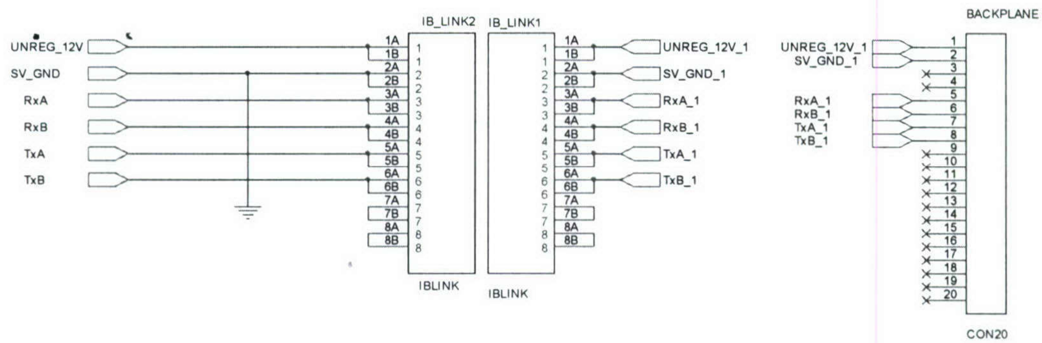


Figure 12 - CAM IB Jumper Board

Layout

The dimensions of the board were specified by the structures team. Using structural drawings, an initial board outline was done. Initially, the board was designed using two layers; however it became apparent that the routing was too complicated and required more versatility. As a result, the board was upgraded to four layers, using a plane layer for ground and 5V. This was still an improvement, however, over the old design which used six layers.
The connectors to the FPGA and backplane were placed first since their locations were specified by the Heron specification. The resulting layout is shown below:

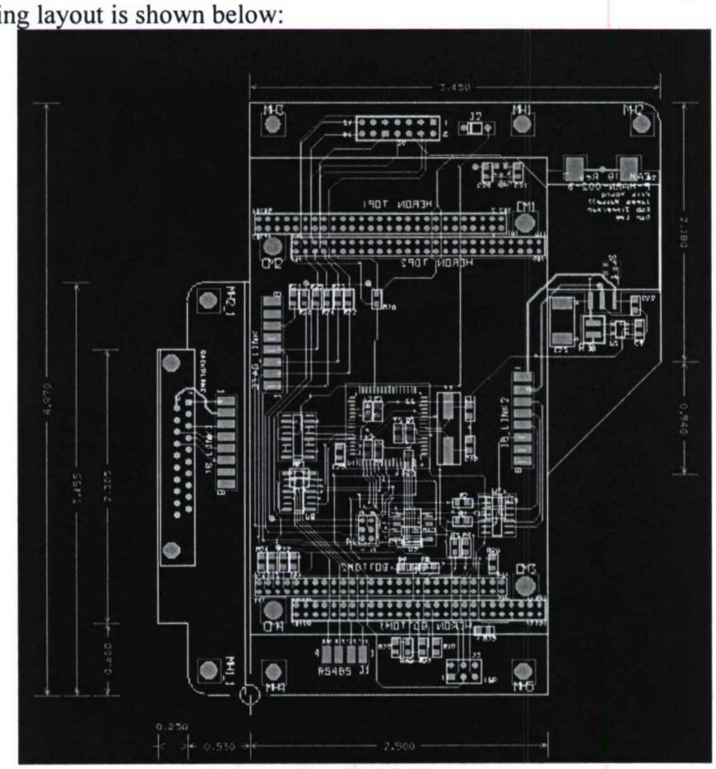


Figure 13 - CAM IB Layout

Power Board Completion

Power Subsystem Circuit Boards

System Requirements

PWR S3. Power distribution shall be centralized.
Source: I&T S2

PWR S3.1. Power shall be capable of toggling the powered state of all other subsystems.

PWR S3.2. Power regulation shall be distributed.

PWR S3.2.1. PWR shall monitor all distribution line voltages.

PWR S3.2.2. PWR shall monitor all distribution line currents.

PWR S4. PWR shall contain the safety inhibits.
Source: UN4-001A Sec. 5.1

PWR S4.1. The safety inhibits shall have double fault tolerance on the positive potential of any power source.

PWR S4.2. While enabled, the safety inhibits shall prevent power flow from any power source on CUSat prior to Launch Vehicle separation.

PWR S4.2.1. Safety inhibits shall be disabled via separation microswitches on the Launch Vehicle Lightband.

[11]

Engineering Work

Upon testing of the FCR power boards, several issues were found with the safety inhibit switches. The safety inhibits consisted of relays designed to prevent powering of the spacecraft before separation. Testing during FCR showed that the FCR design satisfied requirements PWR S6 through PWR S6.22. However, further testing showed that flaws in the design of the safety inhibit circuit prevented the circuit from fulfilling requirement PWR S7.2.1 as the inhibits were never disabled.

The safety inhibits are implemented using four Leach XL-A1A relays. These are high reliability, hermetically sealed relays that latch once they are switched. The relays are initially switched off during launch. After separation from the launch vehicle, microswitches on the separation system will allow current to flow from the solar arrays to the relay coils. The root cause of this was shown to be improper grounding of the circuit, which caused current to flow through the unpowered microcontroller and did not allow the relays to switch. As a result, a new design was required along with a new revision of the power boards.

In addition to fixing the grounding issue, several other optimizations were made. One optimization was the ability to switch off the circuit that drove the inhibit relay coils. This was desired because the coil driver circuit utilized a boost converter that did not need to be powered after the relays flipped. The power draw was significant and noise-inducing, so it was deemed worthwhile to change the design.

The safety inhibits work by prohibiting current flow between power sources and loads. The AFRL requires that there be three independent inhibits between any two power sources or any power source and a load on the positive side and one on the negative side. The diagram below shows how this applies to the CUSat system. The microswitches on the Lightband allow current to flow once separation has occurred. A 28V boost converter (called the "coil driver" in this design) produces a 28V power line for the relay coils. Each separation switch then activates a control line that allows the relay coils to switch using the 28V power line. Once the relays have been activated, the rest of the system receives power. The power system microcontroller can activate an optical isolator to disable the 28V line. Since the relays are latching, the 28V power may be disabled soon after the microcontroller receives power without changing the state of the relays.

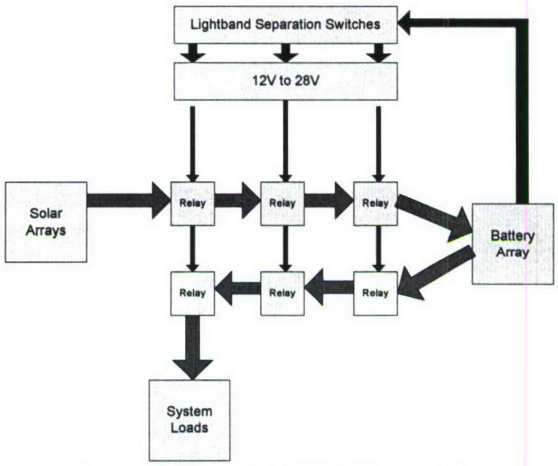
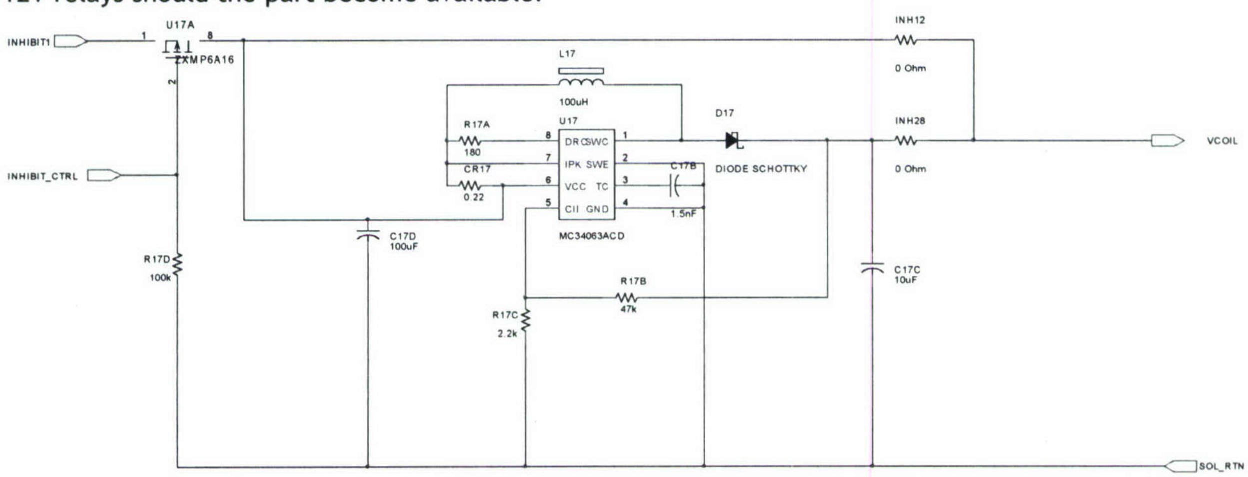


Figure 14 - Safety Inhibit Power Flow

The boost converter used to drive the coils is shown below. The MC34063A is a switch-mode regulator controller. Component values were selected off of the datasheet example. The power supply to the converter is controlled by a MOSFET switch which is normally pulled low (on). The INHIBIT_CTRL line is controlled by the optical isolator in Figure 15. A "do not load" resistor is provided to allow the use of 12V relays should the part become available.



The output capacitor (C17C) was chosen based on part availability. It was difficult to find larger capacitors qualified for space use with high enough voltage ratings. The low value implies there will be notable ripple voltage on the line. This is approximately equal to the RC decay on the line between switching cycles:

$$V_{ripple} = V_0 \left(1 - e^{-\frac{1}{RCf}}\right)$$

Where V_0 is the output voltage, in this case 28V, R is the approximate impedance of the relay coils, and f is the switching frequency of the coil driver. The coils have a rated resistance of 760 Ohms. Since there are four of them in parallel, R is approximately 190 Ohms. f is defined by C17B as per the datasheet of the controller chip and is approximately 40kHz. This gives a ripple voltage of about 0.4V or 0.8V peak-to-peak. This is well within the switching tolerance of the relays.

Relay coils are driven by the 28V line and are controlled by MOSFET switches on the low side. These switches are pulled low (off), but are activated by the Lightband microswitches. An optical isolator allows the microcontroller to control the INHIBIT_CTRL line as discussed earlier. The optical isolation removes grounding concerns that caused the original failure of the system.
Note that although the ground return lines of all power sources need to be disconnected before separation, 10 MOhm resistors are used to prevent buildup of static charge.

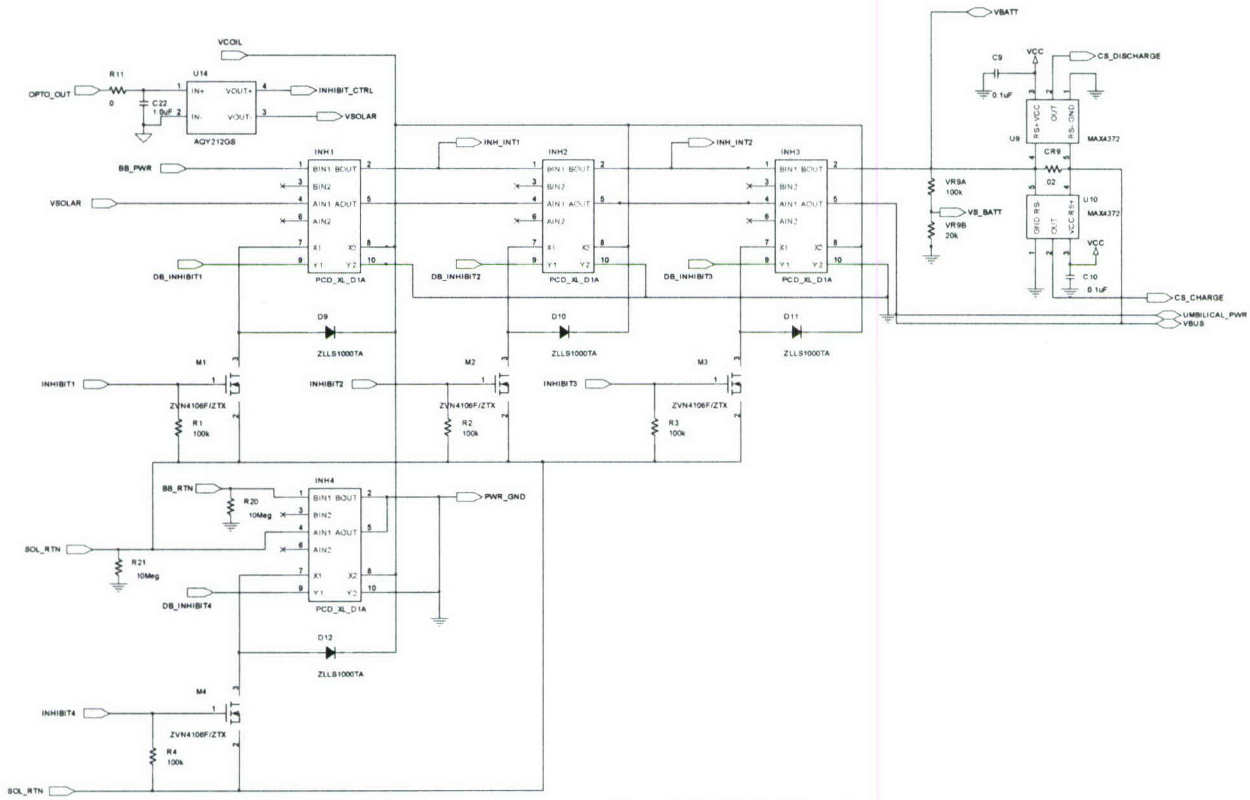


Figure 15 - Power Board Inhibit Circuit

Changes to the schematic were large enough to force a complete re-layout of the power boards. Complete schematics and layout pictures are included in the appendix.

System Level Trade Studies and Analysis

This section explains several system level trade studies that were completed as part of the project.

Solar Panels

System Requirements

PWR S5. Power shall use solar cells.

PWR S5.1. Solar cells shall provide the necessary power to charge the batteries.

PWR S5.2. Solar cells shall provide the necessary power to the spacecraft during illumination.

[11]

Design Trades

Two options were available for solar panel development. The first involved in-house construction of the panels from high-efficiency cells. The second involved an outside manufacturer that used lower efficiency cells. Major decision factors included cost, ease of integration, risk, and power generation. The cell dimensions also mattered in terms of ease of layout.

Option 1 – Emcore Cells

The cells offered by Emcore were 28% efficient Advanced Triple Junction cells. These cells were small (3cmx4cm) allowing for easy placement on the panels. Honeycomb material would need to be ordered as a base for the cells. These cells were also very expensive and required a lot of work to fabricate panels [12].

Option 2 – Spacequest

Spacequest, a small satellite part supplier, was able to manufacture the panel assembly for a cost similar to the bare cells from the other suppliers. The cells, however, were of the larger variety (4cmx7cm) and lower efficiency (about 22%). However, this option eliminated the need for expensive honeycomb material.

Simulation

A MATLAB simulation was done to determine the amount of operational time offered by each of the trade options. The results are summarized below.
Solar input power was assumed to be given by the following formula:

$$P = (\mathbf{E} \bullet \mathbf{N}) SAE_{cell}$$

In this equation, P is solar power from a given face of the satellite. **E** is a normalized vector pointing from the center of the Earth to the sun. **N** is the face normal vector. S is solar intensity (1353 W/m^2) in Low-Earth Orbit. A is the area of the face covered by solar cells. E_{cell} is the solar cell efficiency. Faces that generate a negative solar power were ignored since this indicated that the faces were in shadow.
Code was written in MATLAB to calculate power generation over several orbits. This simulation is also explained in the CUSat power budget document. The MATLAB code is also included in the appendix.
Albedo power, power generated from light reflecting off of the Earth's surface, was ignored for this simulation. While the functionality is included in the simulation, at the recommendation of the AFRL, this was assumed to generate zero power.

The simulation assumed an orbit normal pointing scheme as specified in the Concept of Operations. Results were plotted based on inclination angle and time of year. Parameters such as cell efficiency, battery efficiency, and cell placement were taken into account.

To calculate expected power consumption, several assumptions were necessary. One such assumption was the efficiency of the battery array. From work in earlier semesters (detailed in the CUSat Power Analysis document), this value was estimated at 80%. In other words, 80% of energy used to charge the batteries was assumed to be recoverable from the cells.

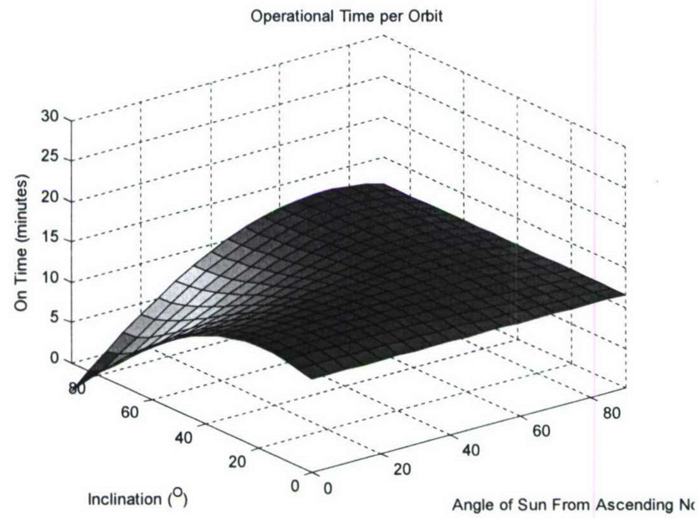


Figure 16 - Spacequest Power Simulation

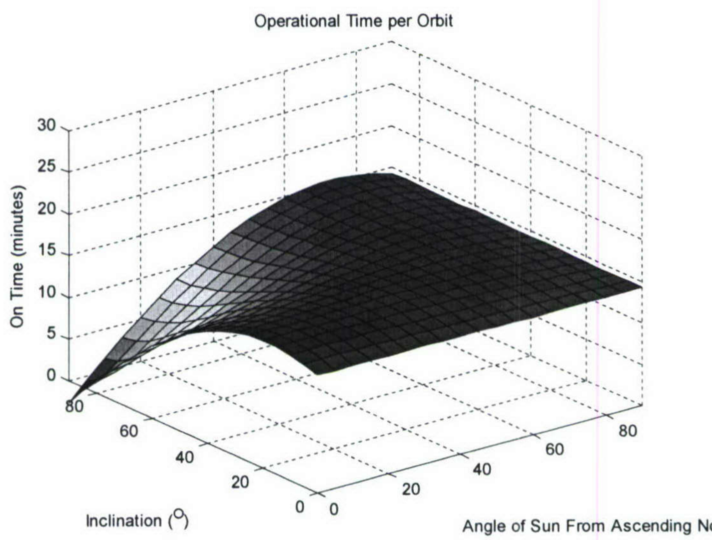


Figure 17 - Emcore Power Simulation

The resulting operational times were fairly similar, with only several minutes difference per orbit of operational time.

Decision

In the end, the decision was made to go with Spacequest for solar cell supply. While the cell efficiency was lower, the power simulation showed that the mission was not significantly affected by the loss of power. The reduced cost, schedule risk, and technical risk far outweighed the reduced power availability.

Communication Antennas

Design Trades

The Telemetry and Command (T&C) subsystem had wrestled with different options for antenna design for a very long time. The original design called for a wire loop antenna on the top and bottom of the spacecraft. During the fall of 2006, the team members decided to design a patch antenna using a dielectric material to increase efficiency. No one on the team had much technical experience with antenna design, so a system level trade was done to encourage outside participation.

Option 1 – Wire Loop Antenna

A lot of analysis had been done early on with this antenna design. Link budgets and initial gain pattern simulations showed that it would most likely verify requirements. However, no one on the team had the technical expertise to verify these results. This antenna would be simple to construct. Initial concerns with mounting of the antenna were relieved when the AFRL informed the team that epoxy was a sufficient means of affixing the antenna [13].

Option 2 – Patch Antenna

This antenna design was done with help from a contact at Ball Aerospace. The antenna was slightly bigger and harder to manufacture due to the rare dielectric material used. However, the simple PCB-based design was attractive and the gain pattern was well understood.

Decision

The decision was made to return to the original design upon confirmation of the gain pattern and link budget numbers. The patch antenna was found to be nearly impossible to manufacture and was a large burden on the solar panels as it was larger and hard to place.

Propulsion Electronics

Design Trades

The original design of the Propulsion Power Unit (PPU) was based directly off of a heritage design from the Dawgstar program. To generate the 2.8kV required for Teflon ablation, the Dawgstar PPU used a flyback converter circuit. CUSat members attempted to copy this configuration but ran into problems with design of the central transformer. AFRL personnel suggested components from Pico electronics that would be able to generate the high voltages required for CUSat's PPU.

Option 1 – Flyback Converter

This design was reasonably well understood, however design of the transformer had caused continual delays and burnouts of parts. In order to go with this design, the transformer issues would need to be definitively solved.

Option 2 – Pico Electronics Converters

Pico electronics produces high-voltage DC-DC converters. These "magic black boxes" are capable of producing the required voltage to charge the PPU capacitors. These parts were recommended by members of the AFRL. However, availability of parts and space-worthiness were concerns at first. These concerns were later alleviated when it was found that Pico can produce Aerospace quality versions of their parts that meet mil-specs. The cost of these devices was relatively low compared to the unknown costs associated with the transformer.

Decision

In this case, the obvious decision was to go with the devices from Pico electronics. It was a better decision in terms of cost, technical risk, and schedule risk.

Camera Interface Circuit Board

System Requirements

HARN S6. The wiring harness shall interface to COTS devices via interface boards.
Source: Error! Reference source not found.

HARN S6.1. Interface boards shall regulate power for COTS boards.

HARN S6.2. Interface boards shall monitor voltage.

HARN S6.3. Interface boards shall monitor current consumption.

HARN S6.4. Interface boards shall monitor COTS board temperature.

HARN S6.5. Interface boards shall communicate with C&DH.
[11]

Design Trades

The purpose of the Camera Interface Board (CAM IB) is to interface the Heron FPGA, which controls picture capture from the cameras, with the CUSat data bus. The original design of this board had to be scrubbed before FCR because of mislabeling of dimensions on the enclosure. A new board was designed that sat on the side of the box. The trade options were to continue with this design or to replace the box "side-board" as well as the baseboard for the FPGA with a single, less dense board.

Option 1 – CAM IB with "Side-Board"

The side-board design was found to have minor flaws during FCR integration. Most of these flaws were a result of improper pin numbering. While this option would be easy to redesign to remove these errors, it posed several structural issues and required complicated harnessing. It also wasted power by powering an unnecessary base-board for the FPGA.

Option 2 – Replace Baseboard

For this option, a new base-board would be reverse engineered to hold the FPGA. This would eliminate structural concerns of the side-board and also reduce harnessing and power consumption. However, there was significant technical risk as a new board design is always risky.

Decision

The decision was made to use a new base-board design. This required significant technical work on the part of the author. Design details are explained in the Design section. While this increased schedule risk, the technical risk was low and the new design mitigated many outstanding structural and harness-related issues.

Ground Segment and Mission Operations

Requirements

GS S1. The Ground Segment shall be able to command the Flight Computer.
Source: SYS S16; GS F1

GS S2. Multiple ground stations shall be networked together.
Source: Error! Reference source not found.

[11]

Design Trades

There were two software packages available for ground station support. Orbital's MAESTRO was originally donated to the program sometime in 2006. However, the software was difficult to use and set up. The contact at Orbital who had originally offered support had also left the company. L-3 Communication's InControl software seemed easier to integrated and set up, however the software had not yet been obtained by CUSat.

Option 1 – MAESTRO

MAESTO is very well respected, real-time software for satellite control and mission management. CUSat already had two licenses donated at an earlier time. However, the software only ran on Sun Solaris and many attempts by CUSat members to run the software had resulted in little success. Orbital had also lost interest in software support.

Option 2 – InControl

InControl is designed to be high reliability software for fleets of satellites. The software also runs on Windows, which was a big benefit for CUSat members. However, while L-3 was interested in donating the software, we had no official guarantee that this would go through.

Decision

It was decided that CUSat would use InControl for ground segment control. The features and support far outweighed the risks associated with using MAESTRO. L-3 representatives were very helpful and the license donation went through quickly.

Results

Hardware Delivery

Flight delivery was originally scheduled for January 2008. The AFRL decided to push this date back to March 2008 to accommodate software delivery with the hardware. However, the original plan of hardware delivery by January is still a goal of the program. TABLE XXX shows the status of hardware deliverables as of the writing of this report.

Table 2 - Hardware Status

	Status	Description
Electronics		
Arcom Vipers	Delivered	
GPS Boards	Delivered	
GPS IB	Delivered	
CDH IB	Delivered	
CAM IB	Testing EDU	The parts are in house. Once the design is verified, the flight units will be assembled.
Power Harnessing	Delivered	
Power Distribution	Delivered	
T&C Control Board	Being Refabricated	Design is verified. Boards need to be refabricated due to population error.
Propulsion Control	Ordered	Need to verify design and build flight units once the parts come in.
Propulsion Power	Ordered	Need to verify design and build flight units once the parts come in.
Propulsion D/I	Ordered	Need to verify design and build flight units once the parts come in.
Camera FPGAs	Needs Flight Prep	Connectors need to be replaced.
HAM Radios	Needs Flight Prep	Needs to be disasembled and prepared for integration. Parts are in house.
Cameras	Ordered	Waiting on order.
Diagnostic Board	Needs Redesign	Current revision works for ground support, but a new version is desired.
Mechanical		
CDH Box	Delivered	
CAM Lid	Delivered	
Top Wall	Delivered	
Bottom Wall	Delivered	
Side Walls	Delivered	
HAM Box	Delivered	
Stiffener	Delivered	
PPTs	Need to make nozzles	Waiting on Ultem stock to make nozzles.

Lifting Harness	Not Manufactured
Assembly Base	Delivered
Harnesses	
Periph 1	Waiting on Parts
Periph 2	Waiting on Parts
Periph 3	Under Construction
Periph 4	Waiting on Parts
Camera Data	Waiting on Parts
Power Board-to-Board	Under Construction
Umbillical	Under Construction

For the electronics, the remaining design items are the propulsion boards and the Diagnostic Board. The propulsion boards have been designed and parts have been ordered. Once the parts come in, design verification with a test unit will begin. This process should conclude before the end of the calendar year. After this, assembly of the flight units will begin barring any unforseen problems. The Diagnostic Board (DB) is a lower priority and therefore has been put off until other board work is done. The DB is currently in its second revision. The second revision DB is adequate for testing of almost all spacecraft systems. A third revision, however, is needed to enable easier integration and test of the safety inhibits.

With the exception of the PPT nozzles, all mechanical hardware has been delivered. All hardware has been anodized or alodined as appropriate. Fit checks have been performed on all mechanical hardware. PPT nozzles have been delayed due to processing issues with the Ultem stock. Once the Ultem order goes through and the stock arrives, manufacturing will begin immediately. This will most likely not affect the delivery schedule.

Wiring harness construction has been delayed due to a large delay in the connector part order. These parts will slowly trickle in over the next few weeks. As the parts come in, the harnesses will be constructed. The harness construction schedule puts Periph 3, the Umbilical harnesses, and the power connectors first since these are first on the critical path for flight build and test. These parts should be finished before the end of the calendar year.

Integration and Test

Every effort is being made to ensure that hardware is ready for Integration and Test (I&T) once the spring semester starts in January. Several pieces of flight hardware, including the CDH IB and the Power Boards, have already been run though their official test plans. The remaining hardware testing will be completed in January.

CAM IB

The CAM IB test unit has been populated and design checkout has begun. The IB correctly powers and initializes the Heron FPGA5 board. The IB also correctly implements the interface to the flight computer. The remaining test items include using the board to take a picture and reprogramming the FPGA using the JTAG interface.

The backplane connector receptacle board that was part of the CAM IB needs to be reordered due to pin hole sizing. This should be relatively inexpensive and very low risk.

Power Boards

The power board flight units have been populated and are undergoing testing. The design verification unit successfully passed all tests. The flight boards are currently awaiting loading of the relays and will then be sent to the Survivability team for flight preparations.

Conclusion

Status of the Program

A majority of hardware items have been delivered as of the writing of this report. The ground segment and mission operations teams have made significant progress this semester and will continue to train new team members and develop solutions next semester. With machining of structural parts nearly complete, several of the mechanical engineers will shift focus to vibration analysis and integration work. Most electronics parts should be delivered by the end of the calendar year.

Several items are still at risk:

Table 3 - Risk Assessment

Items at Risk	Schedule	Technical	Personnel	Budget
CAM IB				
Wiring Harness				
Propulsion Electronics				
Propulsion Igniters				
PPT Manufacturing				
T&C Control Boards				
Software Development				
T&C Antenna and Radios				

The CAM IB poses some schedule risk as it is currently behind other boards. The wiring harness has been delayed by a large amount. Additionally, the team lost experienced harness personnel last semester, adding technical risk. The propulsion electronics are far behind schedule compared to the other electronics parts. The igniters are a large risk as they have not yet fired successfully.

PPT manufacturing offers mild schedule risk as it depends on several part orders. The T&C boards are currently behind schedule due to a construction error. Software development is still in early stages, and therefore poses a risk in several categories. The T&C antenna and radios are far behind schedule and offer large technical risks to the program.

Future Work

This winter break will consist of a large push to catch up in terms of electronics. The goal is to deliver all the electronics boards before the year is over. In the spring semester, work will focus on rapid I&T to meet the March deadline. Software work will need to progress to the testing stage where software can be tested on the flight hardware.

Figure 18 shows the overall schedule for next semester.

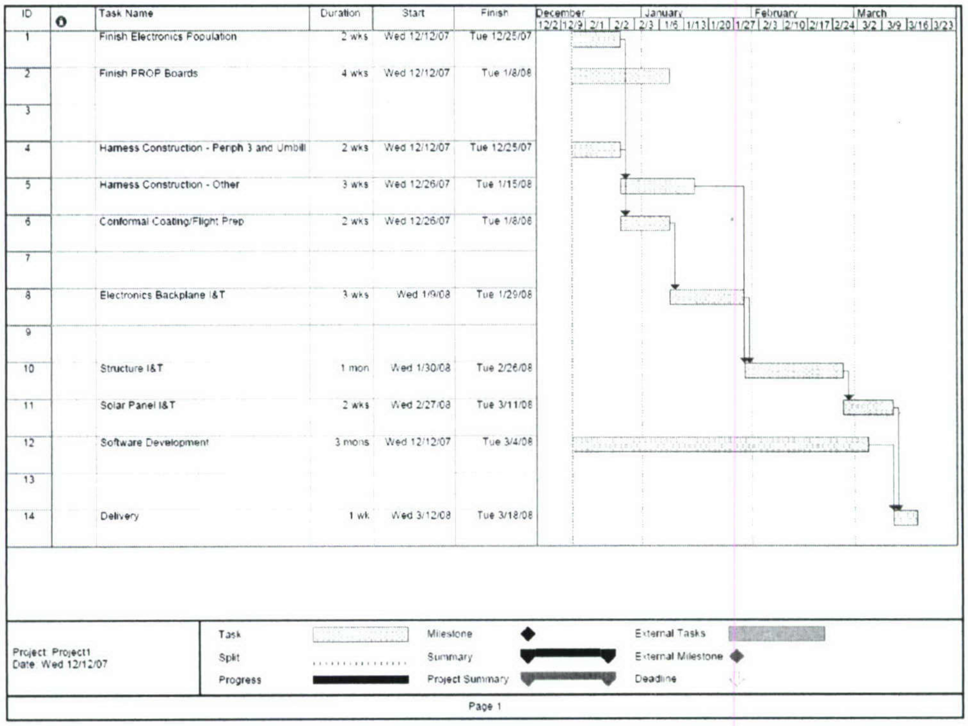


Figure 18 - Forward Looking Schedule

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6. CUSat, Hardware Status Chart, retrieved November 15th, 2007
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8. Hunt Engineering, HERON-BASE1 User Manual Rev. A, January 12, 2001
9. Hunt Engineering, HERON-FPGA5 User Manual Rev. E, May 5, 2005
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11. CUSat, Requirements (CUSAT-SYS-022F), March 6, 2007
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Action Items from Post-FCR Review

ADCNS

- ACS revising, testing
- ADS testing, sun ack
- MOMS SW
- GNC Supervisor
- Lightband delivery, configuration, etc...
- GEONS integration & test
- Position controller
    - Completing orbital design
    - Determine how we do controller
- IMI – upgrade?
    - Stop vibrating!
    - Another supplier?
- Operations
- Spin table
- Software people
- ACS/delta v budget

CAM

- Lens – does it fit in the top panel
- Camera code – 2 cameras
- Calibration procedure
- Lens mounting
- Vibe test
- Mounting bracket didn't line up
- Focal length
- Inter-cam IB connector
- Heater & thermistor mounting
- Replace the base board?
- Mechanical fitting of baseboard

CDH

GS

- Need software people
- Re-contact david schevers
- Doppler compensation w/ TS-2000

GPS

- Receiver code – 2 weeks for passing around
- Capacitors on receivers
- ADS test

MANF

- Paperwork traceability
- Consistency in CM/QA rules
- Top and bottom walls
- Tight lid fits on
- Stiffener
- Alodining parts
- Flight helicoil replacement
- Cam mount hole drills
- 90 degree edges need to go, they need to be rounded
    - Edge rounding spec needs to be made

HARN

- Cam box lid
- Active sync in umbilical
- Harness inventory
- Review by Dale S.
- CAM IB
- CDH IB mount holes
- DB new Rev
- PCB torque values for airborn connectors and how they fit
- CAM harness tools

PWR

- Solar cell design
- Next revision
- Sensors
- Battery box design + assembly
- Lightband boost circuit
- Switches on driver, boost
- 12V relay order
- Centralized distribution
- HAM powering (6V)
- Fault tolerance (cross-strapping)

PROP

PROP-E

- Igniter test
- PPT test in TVC
- Keep current PPU
- DI board needs to be screwed
-

PROP-M

- Particles coming off of PPTs near LV (mission constraint)
- Testing
  - Igniters
  - New PPU
  - EMI
  - Thermal
- Harness design

STR

- Honeycomb panels – ask the AFRL
- Get the FEA model to match the testing
- Wall 2 wall connectors is a crappy design
- Fasteners
  - JSC
  - Ultem
- Alodine/anodize parts, need to research more
- Stand-offs checkout (ultem)
- Battery box, materials
- Lightband people
- Tolerancing analysis
-

SURV

- Materials –
- Conduction pathways
- Testing on working hardware
- Thermal model reflects CONOPS correctly
- Actual thermistor location in e-ics
- Tantalum sheets to kill SEUs

TC

- Kenwood radios EMI w/ PPTs
- SEUs in radio
- Radio – on/off control switch
- HAM box inside the wall
- Radio design
- HAM Radio powering voltage range
- Cabling
- UCF Radio guy

AI&T

- Assy procedures – revise each one
- MGSE needs to be fixed, finished
- Re-structure procedures to help mechanical integration
- Backplane torquing tool
- Need to assess tools for each procedure
- No phillips head screws on spacecraft

System-wide issues

- Lightband POC, lightband contact – Matt Rozek
- Vibe test electronics packaging - Megan
- Grounding architecture – James Maxwell
- Alternate launch configurations – Patrick Conrad
- FEA - Megan

3.0 Personnel Supported

The only paid labor on this program is that of Dr. Jinwoo Lee, a post-doctoral researcher at Cornell, 10% of whose time is paid by the program for his participation as an expert in realtime control and communications electronics.

4.0 Publications

The following publications and presentations have appeared the inception of the project:

K. Young, J. Fikentscher, A. Kelsey, J. Rostoker, O. Eldad, D. Gershman, B. Doyle, K. Graf, and M. Peck, "A GPS-based Attitude Determination System for Small Satellites," 2006 Small Satellite Conference, Logan, Utah, August 14-17, 2006

"The Physics of Very Small Satellites," Miami Museum of Science, Miami, FL, Jan. 23, 2006.

"Systems Architecture for an In-Orbit Inspection Technology Demonstrator," 3rd Mid-Atlantic AIAA Conference, Baltimore, MD., Nov. 5, 2005

5.0 Interactions and Transitions

5.1 Participation and Presentations

Two presentations have come out of this project. Dr. Peck provided a keynote speech at the Mid-Atlantic Regional Conference on November 5, 2005. He presented an overview of the CUSat project, including its connection with responsive-space efforts and NASA's Vision for Space Exploration. Deborah Sunter, the Ground Segment lead, presented her paper on CUSat Concept of Operations.

5.2 Consultative and Advisory Functions

Dr. Peck serves as a consultant in Spacecraft Systems Engineering. In addition to his industry background, his CUSat experience has been brought to bear for consulting with Boeing Satellite Systems, where engineers are creating a process for training in requirements development. His contributions include proposing an object-oriented requirements-allocation process, the same one used on CUSat. The Applied Physics Lab may also bring in Dr. Peck for consulting activities related to classified nanosatellite project proposals. Those discussions are ongoing. Dr. Peck also recently served on a panel reviewing the spacecraft design project for final-year students at the Naval Postgraduate School.

5.3 Transitions

CUSat's innovative use of CDGPS for attitude and navigation is being considered for adoption by Northrop Grumman Space Systems. They are collaborating with Cornell in the development of a responsive ground segment for inspection-related data products. These promising collaborative possibilities add value to the CUSat project and provide encouragement to the students.

6.0 Inventions and Patent Disclosures

CUSat has not patented its technologies.